

PID Routines for MC68HC11K4 AND MC68HC11N4 Microcontrollers

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INTRODUCTION

PID (proportional, integral, derivative) compensation is one of the most common forms of closed-loop control. Control of closed-loop systems that require compensation is a growing area of application for embedded microprocessors. In these systems, analog signals must be converted into discrete digital samples before compensation or filtering can take place. Loop performance dictates the sampling rate, and calculations must be complete before the next sample time begins. These loop-related constraints and the Nyquist frequency requirement place an upper bound on digital control of closed systems with feedback error. If the controlled system has a resonance or other behavior with a time constant shorter than the sample and calculation time, chaos is the most likely outcome. Despite these limitations, increases in microprocessor clock rates and the addition of on-chip control-oriented hardware are expanding the number of medium performance control applications handled by 8-bit machines. While an expensive DSP-class processor is the correct choice for the most demanding applications, several members of the M68HC11 family have the speed and resources to control multiple PWM channels.

This note provides two working examples of PID control-loop software. The first example, written primarily in C, shows a PID algorithm in a straightforward way using floating-point math. Key features of the C environment are covered for readers who are more used to assembly language. The second example implements a PID algorithm in assembly language. It uses the MC68HC11N4 on-chip math coprocessor to speed up arithmetic operations.

Both examples are complete and ready to run on a Motorola M68HC11EVS evaluation board. External interfacing is identical for both examples — an 8-bit analog to digital converter is used for input, and an 8-bit PWM waveform is output. Because the code in both examples carries more than 16 bits of precision, and because both processors support 16-bit PWM, only minor changes are needed to increase precision. Power amplifiers, sensors, and other interface circuitry must be supplied in order to experiment with real-world systems — a simple RC circuit is used for software checkout.

C and assembly language source code and loadable object code can be obtained by calling the Motorola FREEWARE Bulletin Board Service at (512) 891-3733. The FREEWARE BBS operates 24 hours a day, 7 days a week, except for brief periods when it is down for maintenance. The BBS serial format is 300-2400 BAUD, 8 data bits, 1 stop bit, and no parity.



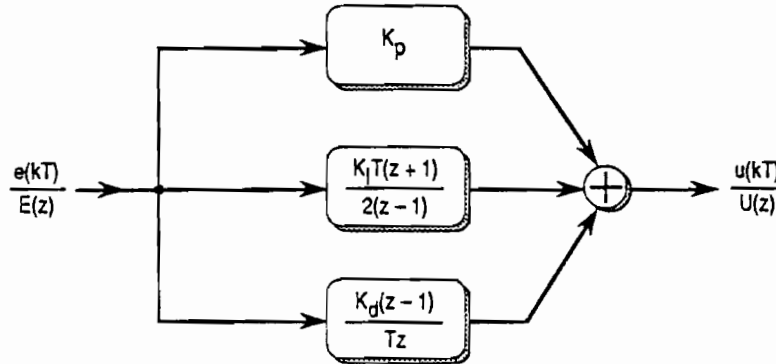
THE MICROCONTROLLERS

The MC68HC11K4 and MC68HC11N4 are 16-MHz devices with nonmultiplexed external address and data buses. Each has 24 Kbytes of on-chip ROM or EPROM. Both devices have multiple PWM channels with programmable period, duty cycle, polarity, and clock source. In both, two 8-bit channels can be concatenated to generate a 16-bit PWM output. The MC68HC11N4 also has two additional 12-bit PWM channels and two digital to analog converter channels with 8-bit resolution.

The MC68HC11N4 is particularly well-suited to PID computation because it has an on-chip math coprocessor that performs 16- and 32-bit multiplication and division, fractional division, and multiply-and-accumulate operations. All operations are done by means of memory-mapped registers, thus preserving the standard M68HC11 family instruction set. Multiplication and fractional division are complete in a maximum of 5 microseconds while integer division requires a maximum of 8.75 microseconds.

PID ALGORITHM

The general flow of a controlled system with PID compensation is shown in Figure 1. References 2 and 3 provide a complete analysis of digital PID control, but it is worthwhile here to informally review the derivation of the discrete forms of each term and how they function.



DIGITAL PID BLOCK

Figure 1. PID Flow Diagram

There is a desired setpoint in our process (G_d) and a measurement of the actual value $G(t)$ in time. Error is:

$$e(t) = G_d - G(t)$$

Output correction $x(t)$ for the PID controller is:

$$x(t) = KP e(t) + KI \int e(t) dt + KD \frac{de(t)}{dt} \Big|_{t=T}$$

where KP , KI , and KD are constants.

Now, rewriting the integral:

$$x(t) = KP e(t) + KI \int_{t=0}^t [G_d - G(t)] dt + KD \frac{de(t)}{dt} \Big|_{t=T}$$

To introduce discrete time, let $t = kT$ where $k = 1, 2, \dots, n$ and $T =$ the sampling and control update period. Now, $t_0 = (k-1)T$. The integral evaluated from $(k-1)T$ to kT can be approximated using the trapezoidal integration rule. The derivative of the error term is simply the rate of change of error, but this can be noisy over one period. Using a four-point central-weighted average for the difference term is a practical way to deal with this on a microprocessor.

The form which can be executed directly on the microprocessor is:

$$x(t) = KP e(t) + KI \left(G_d t - \frac{T}{2} (G(kT) + G[(k-1)T]) \right) + \frac{KD}{6T} ((e(kT) - e(k-3)) + 3(e(k-1) - e(k-2)))$$

This term is added to the current output and put into the PWM control register at the beginning of the next calculation cycle. Substituting the microcode labels for constants and variables into EQ. 4 and using C language operator notation gives:

$$\text{NEWDTY} = KP * (\text{ERRX}) + KI * \text{PERDT} * (\text{CMNDX} - (\text{ADRCX} + \text{ADRCXM1}) / 2) + (KD / (6 * \text{PERDT})) * ((\text{ERRX} - \text{ERRM3X}) + 3 * (\text{ERRM1X} - \text{ERRM2X})) + \text{OLDDTY}$$

The function of the proportional term is clear, but the derivative and integral terms may need a brief explanation. When a system with only proportional control is off the specified setpoint, the controller will increase the control voltage until the error signal is zero, and the system thus returns to the setpoint with more applied voltage than is required for maintaining equilibrium. This causes overshoot and, as the process continues, under-damped ringing. The derivative term contributes proportionally to the error rate of change, but with the opposite sign of the proportional term. If the proper constants are chosen, critical damping can be achieved. The role of the integral term is to eliminate steady state error. A system that has a steady state error when tracking a ramping input function can use an integral term to integrate the error over time and compensate for it.

C LANGUAGE IMPLEMENTATION

This version of the PID control routine illustrates use of high-level language for control applications. High-level language offers many conveniences not available in assembly language. Here are a few instances:

Memory-mapped registers can be defined in a single file, which can be included in any function.

Since C is a strongly-typed language, the compiler can identify data-type mismatches, such as writing a 16-bit integer to an 8-bit port.

Most C compilers for the M68HC11 family allow direct vectoring to interrupt service routines. Interrupt functions are usually defined for a special memory segment with a base address and a function name:

```
interrupt [INTVEC_START + 26] void RTI_interrupt(void);
```

When an interrupt service routine is written it can be declared as an interrupt function instead of a normal subroutine:

```
interrupt void RTI_interrupt(void)
```

The function is compiled with a terminating RTI instruction, eliminating the need for a patch between hardware interrupts and C subroutines. The void statements indicate that no arguments are being passed to or from the interrupt routine.

One of the most attractive features of contemporary C compilers is the ability to add floating point math with an "include math.h" statement. Even when the final application can't afford the time or code space for floating point calculations, use of floating point math during debugging provides an excellent means of testing new algorithms.

Now to examine the control routine itself (refer to Appendix A for a complete C listing). After necessary files are included and floating point variables are declared, a prototype is given to define an assembly language function that is used later.

The main program initializes constants and variables, sets up the required on-chip peripherals, and waits for interrupts to occur. The M68HC11 real-time interrupt (RTI) is used to establish a precise time base for performing PID compensation. The period (T or PERDT) is determined by the RTI rate. In these examples, the period is 16.383 milliseconds, but this value is arbitrary — in real applications, the performance of the controlling microprocessor and the requirements of the controlled system determine the period.

The RTI_interrupt function is a workhorse. It does PID loop PWM duty cycle calculations, performs I/O using the DOIO assembly language function, and checks the results against the usable PWM output range of \$00 to \$FF. If a floating-point result is out of range, the closest limit is substituted. This "saturation arithmetic" prevents out-of-range results from causing sign-reversals in the PWM output.

Details of error-checking and the DOIO subroutine are best understood by looking at the format of the floating-point variables. The four byte format is:

```
SEEEEEEE EMMMMMMM MMMMMMMM MMMMMMMM
```

S represents a sign bit, E represents an 8-bit exponent biased by 127, and M represents a 23-bit fractional mantissa (significand) with an implicit leading 1. The I/O range of \$00 to \$FF is scaled into the eight most significant bits of a floating-point variable, giving a floating-point range of 1.0 (\$3F800000) to 1.998046875 (\$3FFF8000). The following expression is used to evaluate a floating-point number:

$$F = [(-1)^S] [2^{(E-127)}] [1.M]$$

When the RTI_interrupt function returns control to the C routine, the last task the routine must perform is preparation for the next period. A two-element pipeline of the A/D reading and a four-element error pipeline are updated. Finally the "old" duty cycle value is copied into OLDDTY.

MC68HC11N4 MATH COPROCESSOR

The assembly PID routine uses the MC68HC11N4 math coprocessor, which is commonly referred to as an arithmetic logic unit, or ALU. A brief description of the coprocessor will aid in understanding how the routine functions.

The ALU performs 32/16-bit division, 16/16 multiplication, multiply-and-accumulate operations, and 16/16-bit fractional division without CPU intervention. The coprocessor has one control register, one status register, and three data registers. The 8-bit ALU control register (ALUC) controls ALU operation. The 8-bit ALU status register (ALUF) signals when an operation is complete and indicates the status of the completed operation. Data register A (AREG) can hold either a 16-bit multiplicand or a 16-bit divisor. Data register B (BREG) can hold either a 16-bit multiplier or a 16-bit remainder after division. Data register C (CREG), which is treated as two 16-bit registers (CREG High and CREG Low), can hold a 32-bit product or accumulated product after multiplication, or it can hold a 32-bit numerator before division and a 32-bit quotient after division. There is an implied fixed radix point to the right of bits AREG0, BREG0, and CREG0.

Figure 2 shows coprocessor registers. Arrows indicate the most convenient order of writing the registers. A description of ALUC and ALUF bit functions follows. Figure 3 shows typical data register formats. Table 1 shows numeric ranges of ALU registers. Table 2 shows signed expression of numbers. Table 3 shows fractional numeric representation.

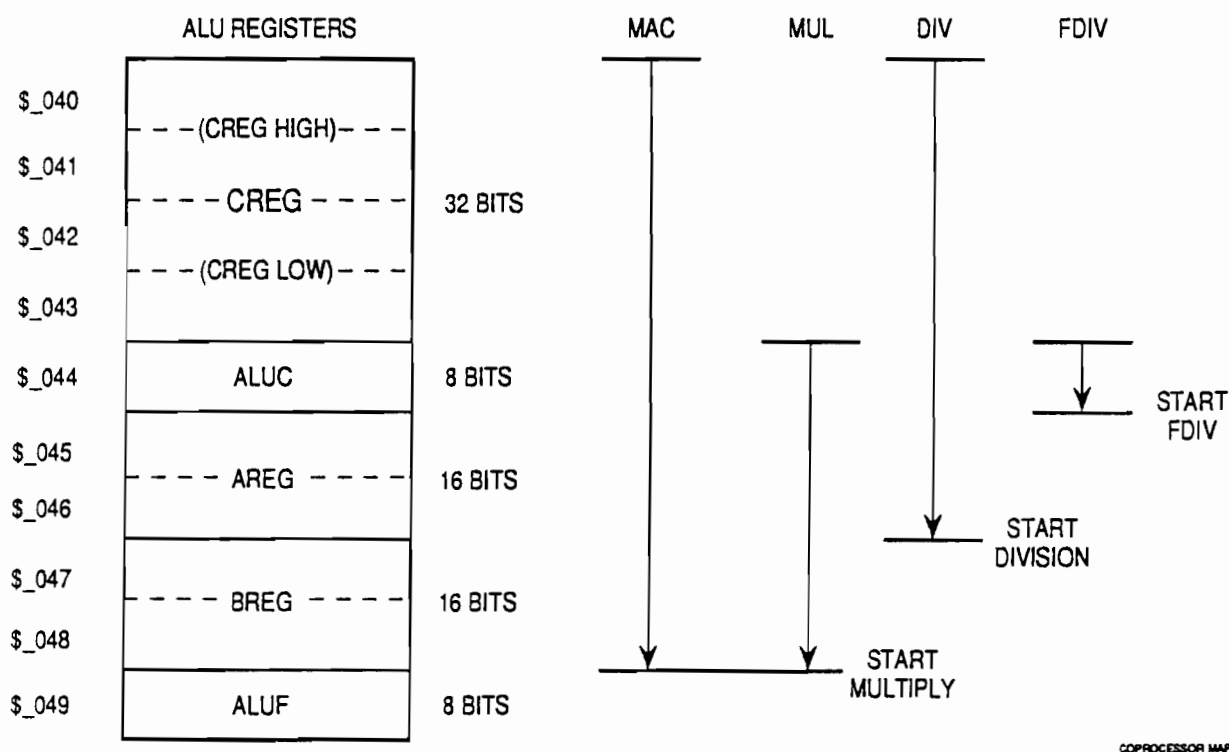


Figure 2. Coprocessor Registers and Operations

ALUC — Arithmetic Logic Unit Control

\$0044

	Bit 7	6	5	4	3	2	1	Bit 0
	SIG	DIV	MAC	DCC	TRG	—	—	—
RESET:	0	0	0	0	0	0	0	0

SIG — Signed Number Enable

0 = AREG, BREG, and CREG contents are unsigned numbers

1 = AREG, BREG, and CREG contents are signed numbers

DIV — Division Enable

MAC — Multiply with Accumulated Product Enable

DCC — Division Compensation for Concatenated Quotient Enable

TRG — Function Start Trigger Bit

Always reads zero

0 = No effect

1 = Start ALU

Bits [2:0] — Not implemented

Always read zero

SIG	DIV	MAC	DCC	FUNCTION	START TRIGGERS
0	0	0	X	Unsigned MUL	Write BREG or set TRG
1	0	0	X	Signed MUL	Write BREG or set TRG
0	0	1	X	Unsigned MAC	Write BREG or set TRG
1	0	1	X	Signed MAC	Write BREG or set TRG
0	1	0	X	Unsigned IDIV	Write AREG or set TRG
1	1	0	0	Signed IDIV	Write AREG or set TRG
1	1	0	1	Signed IDIV DCC	Write AREG or set TRG
0	1	1	X	Unsigned FDIV	Set TRG
1	1	1	0	Signed FDIV	Set TRG
1	1	1	1	Signed FDIV DCC	Set TRG

ALUF — Arithmetic Logic Unit Status Flag Register

\$0049

	Bit 7	6	5	4	3	2	1	Bit 0
	NEG	RZF	—	—	—	OVF	DZF	ACF
RESET:	0	0	0	0	0	0	0	0

NEG — Negative Result

NEG is set if the result is a negative value. This is a read-only-bit. Writes to this bit do not affect the value.

RZF — Remainder Equals Zero Flag

RZF is set if the remainder is zero.

Bits [5:3] — Not implemented

Always read zero

OVF — Overflow Flag

OVF is set if overflow from MSB on CREG is detected. This bit is cleared automatically by a write to this register with bit 2 set.

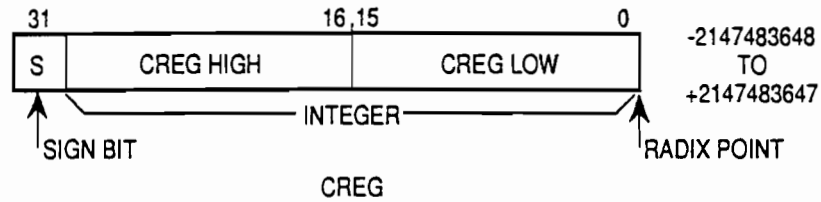
DZF — Divide by Zero Flag

DZF is set if a divide by zero condition is detected. DZF is cleared automatically by a write to this register with bit 1 set.

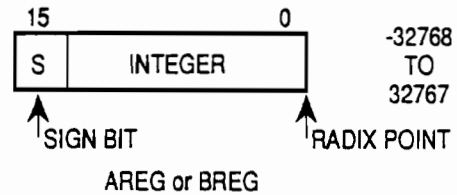
ACF — Arithmetic Completion Flag

ACF is set by completion of the arithmetic operation. ACF is cleared automatically by a write to this register with bit 0 set.

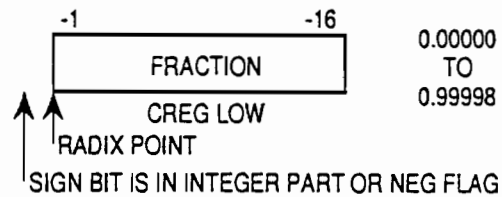
32-BIT SIGNED INTEGER NUMBER



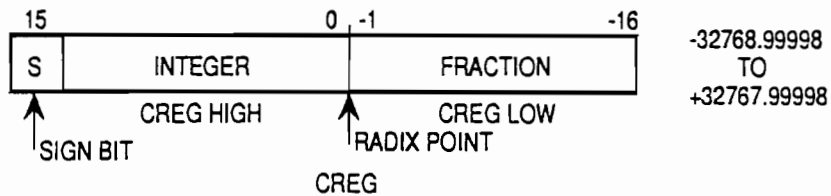
16-BIT SIGNED INTEGER NUMBER



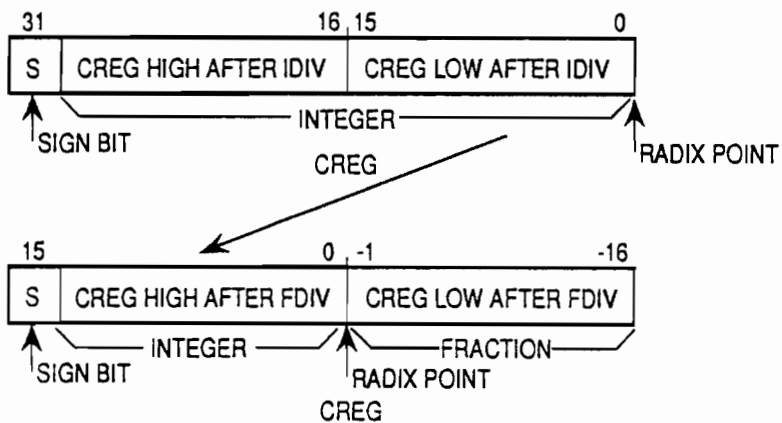
16-BIT FRACTION NUMBER AFTER FDIV



32-BIT SIGNED INTEGER AND FRACTION FOLLOWING AN FDIV



LONG WORD SIGNED RESULT AFTER FDIV FOLLOWING AN IDIV



COPROCESSOR
REG FORMAT

Figure 3. ALU Data Register Format

Table 1. Numeric Ranges of ALU Registers

Register	Size	Unsigned	Signed
AREG	16 bits	0 to 65535	-32,768 to +32,767
BREG	16 bits	0 to 65535	-32,768 to +32,767
CREG	32 bits	0 to 4,294,967,295	-2,147,483,648 to +2,147,483,647

Table 2. Signed Numbers

Decimal	16-Bit Hexadecimal	32-Bit Hexadecimal
+2,147,483,647	—	\$7FFF FFFF
.	—	.
.	—	.
+32,767	\$7FFF	\$0000 7FFF
.	.	.
.	.	.
+1	\$0001	\$0000 0001
0	\$0000	\$0000 0000
-1	\$FFFF	\$FFFF FFFF
-2	\$FFFE	\$FFFF FFEE
.	.	.
.	.	.
-32,768	\$8000	\$FFFF 8000
.	—	.
.	—	.
-2,147,483,647	—	\$8000 0000

Table 3. Fractions

Decimal	16-Bit Hexadecimal
+0.99998	\$FFFF
.	.
.	.
+0.5	\$8000
+0.25	\$4000
+0.125	\$2000
+0.0625	\$1000
+0.03125	\$0800
+0.015625	\$0400
.	.
.	.
+0.0000153	\$0001
-0.99998	\$0001
.	.
.	.
-0.5	\$8000
-0.25	\$C000
-0.125	\$E000
-0.0625	\$F000
-0.03125	\$F800
-0.015625	\$FC00
.	.
.	.
-0.0000153	\$FFFF

ASSEMBLY LANGUAGE IMPLEMENTATION

The assembly language version of the PID control routine consists of a C master program and an assembly subroutine (DOPID) that carries out all time-critical tasks (see Appendix B for a complete listing). The C master program is used for convenience — DOPID can be made to stand alone with minor changes in variable definition.

The constant and variable number representation for the assembly version of the PID loop is a four-byte number consisting of a 16-bit integer, an implied decimal point, and a 16-bit fraction. This representation was chosen to provide relatively high performance while giving enough precision to support MC68HC11N4 8-, 12-, and 16-bit PWM resolutions. Many other formats could be used, each with a particular trade-off between precision and time.

Although the sampling period constant and the constants of each term of the PID algorithm could be calculated during the assembly phase and set in the final code, these values are instead initialized as ratios of hexadecimal integers, then calculated in real time in the loop. This arrangement allows easy experimentation with these values without reassembling each time a value is changed. The initial format of these values (numerator and denominator) is a consequence of the four-byte numeric representation.

Here are some examples of ALU operations performed during PID computation.

To perform a signed integer divide followed by a signed fractional divide, the numerator is written to CREG, \$C0 is written to ALUC, and the divisor is written to AREG. After the completion flag in ALUF is set (\$49), \$E8 is written to ALUC. Following integer division, the quotient is in CREG and the remainder is in BREG. Fractional division moves the content of CREG Low to CREG High, then places a 16-bit fraction in CREG Low. The final result is a 16-bit quotient in CREG High and a 16-bit fraction in CREG Low. There is an implicit decimal point between CREG High and CREG Low. More precision can be obtained by concatenating fractional divisions.

To perform a signed multiply, \$80 is written to ALUC and multiplicands are written to AREG and BREG. When the operation is complete, a 32-bit result is in CREG.

The actual range used for control is hexadecimal \$0000.0000 to \$00FF.FFFF (decimal 0 to 255.99998). While the error term can be positive or negative, PWM output and feedback voltage are always positive. A result greater than \$FF is treated as an overflow, and a result less than \$00 is treated as an underflow. This effects a saturated value of the correct sign as in the C version. Except for the expression of initial constants as ratios, formula 5 is not changed. In the derivative term the factor

$$(KDNUM / KDDEN) / ((6 * (PERDTNUM / PERDTDEN))$$

is rearranged to

$$((KDNUM / KDDEN) * PERDTDEN) / (6 * PERDTNUM).$$

The DOPID routine is written as straight-line code. Only two subroutines and a limit-checking section are shared by the proportional, integral, and derivative terms. The subroutines MULLNG and ADLNG are used to multiply and add terms and factors expressed in the special four-byte format explained previously. Each of the P, I, and D terms use ADLNG to contribute to the new PWM duty cycle (NEWDTY), but, as in the C version of the PID routine, NEWDTY is not output until the beginning of the next period. Only the 8-bit integer portion is used, and the 1-bit round-off error this causes is not corrected — the effect is negligible in this 8-bit example. After all three terms are calculated, control is returned to the master C routine. The master routine updates the error and A to D pipelines, then enters the main wait loop.

During program execution, all results and most intermediate values are kept in RAM, rather than on the stack. Controller state can easily be inspected by means of a single breakpoint and a dump of the appropriate variable address. Variable addresses are provided in the C startup code for the assembly routine — the addresses are only valid for this compilation and can change with code revision.

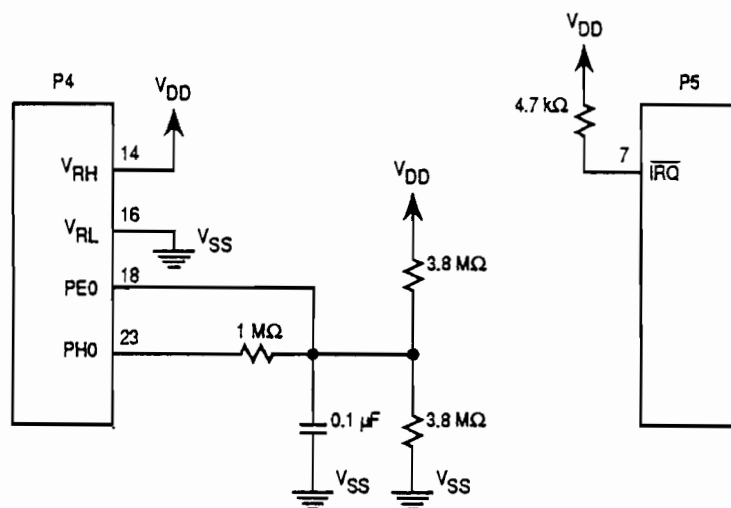
HARDWARE PLATFORM

The Motorola M68HC11KMNPEVS Evaluation System can be used to run both versions of the PID routine. With an MC68HC11K4 inserted in the emulator module, only the floating point version will execute. With an MC68HC11N4 inserted, both versions can be executed — the floating point version simply does not use the math coprocessor.

Both versions of the PID routine utilize special test mode in the EVS system. This means that the M68HC11 processor vectors are mapped from \$BFD6 to \$BFFF instead of from \$FFD6 to \$FFFF, and can be placed in user RAM or in emulation RAM, making experimentation with varied processor configuration options easier. Refer to the *M68HC11KMNPEVS Evaluation System User's Manual* for more information.

S-record formatted object code can be loaded and run on the EVS using appropriate serial communications software. The default EVS Baud rate is 19200 Baud.

A simple RC circuit is used to provide the feedback necessary for the software PID loop to operate. The connections to the EVS are shown in Figure 4. PH0 is the processor PWM output and PE0 is the channel 1 A/D input. Note that the A/D reference inputs must be connected to appropriate supplies and the IRQ line must also be tied high. A two-channel oscilloscope can be used to observe PWM output and controlled voltage. Both versions of the code write \$FF to PORTA just before performing PID loop calculations and then write \$00 to the port just after calculations are complete, allowing execution times to be observed with a scope.



K4 EVS TEST SCHEM

Figure 4. Evaluation System Schematic

PERFORMANCE

Since two very different approaches were taken to implement the PID loop algorithm, it is not surprising that the performance and code sizes of the two routines differ significantly. The C language version contains over 1500 bytes, much of which consists of floating point runtime support. Because it carries full floating-point precision and does not use math support hardware, the C version takes approximately 6 milliseconds to complete the loop. The assembly version contains approximately 1000 bytes, and could be reduced to about 800 bytes if features added for clarity and experimentation were removed. Because it uses a tailored arithmetic format and gets a hardware assist from the math coprocessor, the assembly version completes the loop in approximately 700 microseconds. In both cases, performance could be improved by precomputing all the results with constant factors.

EXPERIMENTS AND EXTENSIONS

To develop a more intuitive understanding of PID loop function, try varying the term constants in the object code and observing the effect on controller performance. For the C version, it is best to change the values in the C source and recompile. For the assembly version, it is easy to recalculate and change denominators of the constants: only decimal-to-hex conversion is required. The PERDT constant must be changed when the RTI interrupt rate is changed, or the time base of the algorithm will be destroyed. Try adjusting the proportional and derivative constants to give good observable control and then start substituting smaller value resistors for R1. Eventually, the substitution will cause an unstable underdamped system.

Many extensions to the routines are simple yet interesting. The command voltage level can be read from one of the seven unused A/D channels to give real-time control points. The MC68HC11N4 version could have analog output instead of PWM with the use of an 8-bit D/A channel. The N4 version could also use an infinite impulse response (IIR) filter implemented by means of the math coprocessor multiply-and-accumulate capability, rather than utilizing the noise-canceling effect of the derivative term's four point central difference.

CONCLUSIONS

With the 16.383 millisecond sampling rate chosen, the floating point C routine cannot service all four MC68HC11K4 PWM channels. It could, however, service one higher-rate channel and several less time-critical processes. The assembly math coprocessor routine can service all the MC68HC11N4 PWM channels (four 8-bit and two 12-bit) in 4.2 milliseconds, leaving 75% of execution time for other tasks. If the MC68HC11N4 D/A channels were also used, six independent PID controllers could be run in 5.6 milliseconds — this routine would use less than a third of the allowable processing time and require only half of the twelve MC68HC11N4 A/D input channels.

The two approaches to PID control outlined in this note encompass a wide range of useful and cost-effective applications. The simplicity of the coded C algorithm is very appealing. Since the C routine carries virtually no code-space overhead, it is very well-suited to an application where floating-point math is already required, and a sampling rate in the 20-millisecond range is acceptable. Because it uses a number format adapted to the application and to use of on-chip resources, the assembly routine generally yields higher, more cost-effective performance than the C routine.

A final word of caution. There is no substitute for thorough mathematical analysis of the system to be controlled in the discrete time domain. References 2 and 3 contain detailed discussions of control systems and analytic techniques.

REFERENCES

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4. Motorola. MC68HC11K4 Technical Summary, BR751/D
5. Motorola. MC68HC11N4 Technical Summary, MC68HC11N4TS/D
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7. Motorola. M68HC11K4EVS Evaluation System User's Manual, M68HC11K4EVS/D1

APPENDIX A

C LANGUAGE PID ROUTINE

A.1 Main C Routine

```
#include <stdio.h>
#include <io6811k4.h>
#include <int6811k.h>
#include <math.h>

zpage unsigned int    TOFCOUNT;          /* declare variables */
zpage float          CMNDVX;
zpage float          ADRCX;
zpage float          ADRCXM1;
zpage float          ADRCXM2;
zpage float          ADRCXM3;
zpage float          ERRX;
zpage float          ERRM1X;
zpage float          ERRM2X;
zpage float          ERRM3X;
zpage float          PERDT;
zpage float          NEWDTY;
zpage float          OLDDTY;
zpage float          KP;
zpage float          KD;
zpage float          KI;

extern int    DOIO (void);                /* prototype for assembly
                                           routine */

void main()                               /* main program */
{
    CMNDVX = 1.5;
    PERDT = 0.016383;                     /* RTI and therefore PID loop period = 16.383 ms */
    KP = 0.18;                             /* kp = .12, ki = 6.0, kd = .006, for 1 M ohm drive */
    KI = 6.0;
    KD = 0.009;
    OLDDTY = 1.9;                         /* start out with pwm set fairly high */
    PORTA = 0x00;                         /* this will be used for a scope trigger */
    DDRA = 0xFF;                          /* set PORTA as output */
    PACTL = 0x03;                         /* set RTI to 16.383 ms (E = 4 MHz) */
    TMSK2 = 0x40;                         /* enable RTI interrupts */
    OPTION = 0x90;                        /* enable A/D charge pump */
    PWPER1 = 0xFF;                        /* set up PWM channel 1 at 15.625 kHz */
    PWDTY1 = 0xFF;                        /* with positive polarity */
    WPPOL = 0x01;
    DDRH = 0x00;
    PWEN = 0x01;
    TFLG2 = 0x40;
    enable_interrupt();                   /* wait here for RTI to cause loop execution */
    wait_for_interrupt();

    for (;;) {
        ;
    }
}
```

```

interrupt void IRQ_interrupt(void) /* should initialize all interrupts... */
{
    PORTA = 0xFF;
    PORTA = 0x00;
}

interrupt void TO_interrupt(void)
{
    TOFCOUNT++;
}

interrupt void RTI_interrupt(void) /*PID LOOP/PWM routine */
{
    PORTA = 0xFF; /* scope strobe */

    DOIO(); /* read A to D and output the duty
             cycle calculated last period */

    ADCTL = 0x10; /* begin new conversion cycle */

    ERRX = (CMNDVX - ADRCX); /* calculate current error */

    /* The statement below is the entire floating point PID loop */

    NEWDTY = KP*(ERRX) + KI*PERDT*(CMNDVX - (ADRCX + ADRCXM1)/2)
             + (KD/(6*PERDT))*((ERRX - ERRM3X) + 3*(ERRM1X - ERRM2X))
             + OLDDTY;

    if (NEWDTY > 1.99609) /* test for result being in usable */
        NEWDTY = 1.99609; /* limits and set PWM duty cycle if */
    else if (NEWDTY < 1.0) /* beyond saturation */
        NEWDTY = 1.0;

    TFLG2 = 0x40; /* clear RTI flag */
    ADRCXM1 = ADRCX; /* update A/D result for next cycle */
    ERRM3X = ERRM2X; /* update error pipeline */
    ERRM2X = ERRM1X;
    ERRM1X = ERRX;
    OLDDTY = NEWDTY; /* update old duty cycle for next
                     calculation period */

    PORTA = 0x00; /* scope strobe */
}

```

A.2 DOIO Subroutine Assembler Listing

```

1          *****
2          *      DOIO assembly function      *
3          *      This routine handles the conversion between      *
4          *      8 bit register values and the C float variables *
5          *
6          *****
7
8 0000          MODULE DOIO
9 0000          PUBLIC DOIO
10
11 0000          P68H11
12 0000          RSEG CODE
13
14 006C          PWDY1 set $006C          REGISTER LOCATIONS
15 0031          ADDR1 set $0031
16 0000          EXTERN ADRCK:ZPAGE      EXTERNAL VARIABLE LOCATIONS
17 0000          EXTERN NEWDY:ZPAGE
18 0000          DOIO:
19 0000 863F          LDAA #$3F
20 0002 5F          CLR B
21 0003 D000          STD ADRCK          INITIALIZE FLOAT LOCATION.
22 0005 9631          LDAA ADDR1          GET CHANNEL 1 A/D RESULT.
23 0007 04          LSR D          SHIFT TO FLOAT MANTISSA POSITION.
24 0008 8A80          ORAA #$80          OR IN LEAST SIGNIFICANT EXP BIT
25 000A D001          STD ADRCK+1          AND STORE IT IN FLOAT VARIABLE.
26 000C 5F          CLR B          CLEAR LEAST SIGNIFICANT
27 000D D703          STAB ADRCK+3          FLOAT BYTE.
28 000F DC01          LDD NEWDY+1          GET TWO BYTES OF FLOAT MANTISSA.
29 0011 05          LSL D          SHIFT TO CORRECT REGISTER POSITION.
30 0012 976C          STAA PWDY1          OUTPUT TO PWM DUTY REGISTER.
31 0014 39          RTS
32 0015          END

```


APPENDIX B

ASSEMBLY LANGUAGE PID ROUTINE

B.1 Master C Routine

```
/* This code just sets up variables and does some updates
   after the assembly PID loop is called. */
```

```
#include <stdio.h>
#include <io6811N4.h>
#include <int6811N.h>
```

```
zpage  unsigned int    TOFCOUNT;          /* declare variables */
zpage  signed int      CMNDVX;
zpage  signed int      ADRCX;
zpage  signed int      ADRCXM1;
zpage  signed int      ERRX;
zpage  signed int      ERRM1X;
zpage  signed int      ERRM2X;
zpage  signed int      ERRM3X;
zpage  signed int      KPNUM;
zpage  signed int      KPDEN;
zpage  signed int      KINUM;
zpage  signed int      KIDEN;
zpage  signed int      KDNUM;
zpage  signed int      KDDEN;
zpage  signed int      PERDTNUM;
zpage  signed int      PERDTDEN;
zpage  signed int      INTS6;
zpage  signed int      FCS6;
zpage  signed int      TEMP1;
zpage  signed int      TEMP2;
zpage  signed int      TEMP3;
zpage  signed int      TEMP4;
zpage  long           NEWDTY;
zpage  long           OLDDTY;
zpage  long           KPTRM;
zpage  long           KDTRM;
zpage  long           KITRM;
zpage  long           LTEMP1;
zpage  long           LTEMP2;
zpage  long           LTEMP3;
zpage  long           LTEMP4;
zpage  long           LTEMP5;
zpage  long           LTEMP6;
zpage  long           LTEMP7;
zpage  long           LTEMP8;
zpage  long           LTEMP9;
zpage  long           LTEMPA;
zpage  long           FCINTS6;
zpage  long           INTFC56;
```

```
extern int  DOPID (void);
```

```
/* prototype for assembly
   routine */
```

```

void main()                /* main program */
{
    CMNDVX = 0x0080;
    PERDTNUM = 0x00A4;
    PERDTDEN = 0x2710;      /* PERIOD = 164/10000 decimal */
    KPNUM = 0x000C;
    KPDEN = 0x0064;        /* kp = .12, ki = 6.0, kd = .006, for 1M ohm drive */
    KINUM = 0x0006;
    KIDEN = 0x0001;
    KDNUM = 0x0006;
    KDDEN = 0x03E8;
    OLDDTY = 0x00FF0000;
    PORTA = 0x00;
    DDRA = 0xFF;           /* set PORTA as output */
    PACTL = 0x03;          /* set RTI to 16.383 ms (E = 4MHz) */
    TMSK2 = 0x40;          /* enable RTI interrupts */
    OPTION = 0x90;          /* enable A/D charge pump */
    PWPER1 = 0xFF;          /* set up PWM channel 1 at 15.625 kHz */
    PWDTY1 = 0xFF;          /* with positive polarity */
    PWPOL = 0x01;
    DDRH = 0x00;
    PWEN = 0x01;
    TFLG2 = 0x40;

    enable_interrupt();     /* wait for RTI to execute assembly PID routine */

    wait_for_interrupt();

    for (;;) {
        ;
    }

    interrupt void IRQ_interrupt(void) /* Just some traps for unexpected */
    {                                  /* interrupts */

        PORTA = 0xFF;
        PORTA = 0x00;
    }

    interrupt void TO_interrupt(void)
    {
        TOFCOUNT++;
    }

    interrupt void RTI_interrupt(void) /* PWM routine */
    {
        PORTA = 0xFF;           /* scope strobe */
        DOPID();                /* DO THE PID LOOP USING THE MATH
                                COPROCESSOR */

        /* NEWDTY = KP*(ERRX) + KI*PERDT*(CMNDVX - (ADRCX + ADRCXM1)/2)
           + (KD/(6*PERDT))*((ERRX - ERRM3X) + 3*(ERRM1X - ERRM2X))
           + OLDDTY; */

        TFLG2 = 0x40;           /* clear RTI flag */
        ADRCXM1 = ADRCX;         /* update A/D result for next cycle */
        ERRM3X = ERRM2X;         /* update error pipeline */
        ERRM2X = ERRM1X;
        ERRM1X = ERRX;
        PORTA = 0x00;           /* scope strobe */
    }
}

```

B.2 DOPID Assembly Listing

```

1          *****
2          *   DOPID assembly function   *
3          *   These routines calculate the new PWM duty cycle   *
4          *   using the MC68HC11N4 math coprocessor.  The      *
5          *   code can be run on an M68HC11EVS with an          *
6          *   M68HC11K4 emulator and MC68HC11N4 processor.     *
7          *   The EVS monitor should be 1.1 or later. The EVS  *
8          *   and vectors were set to SPECIAL TEST MODE to aid debug. *
9          *   This code is called by a C routine but could be converted *
10         *   to an all assembly environment by defining the variables *
11         *   in assembly instead of as externals.              *
12         *****
13
14 0000          MODULE  DOPID
15 0000          PUBLIC  DOPID
16
17 0000          P68H11
18 0000          RSEG    CODE
19
20 006C          PWDTY1  set      $006c
21 0030          ADCTL   set      $0030
22 0031          ADR1    set      $0031
23 0040          CREGH   set      $0040
24 0041          CREGMH  set      $0041
25 0042          CREGML  set      $0042
26 0043          CREGL   set      $0043
27 0044          ALUC    set      $0044
28 0045          AREGH   set      $0045
29 0046          AREGL   set      $0046
30 0047          BREGH   set      $0047
31 0048          BREGL   set      $0048
32 0049          ALUF    set      $0049
33
34
35
36
37 0000          EXTERN  ADRCX:ZPAGE          $0084  EXTERNAL VARIABLES
38 0000          EXTERN  ADRCXM1:ZPAGE        $0086  SIGNED INTS
39 0000          EXTERN  CMNDVX:ZPAGE          $0082
40 0000          EXTERN  ERRX:ZPAGE           $0088
41 0000          EXTERN  ERRM1X:ZPAGE          $008A
42 0000          EXTERN  ERRM2X:ZPAGE          $008C
43 0000          EXTERN  ERRM3X:ZPAGE          $008E
44 0000          EXTERN  KPNUM:ZPAGE           $0090
45 0000          EXTERN  KPDEN:ZPAGE           $0092
46 0000          EXTERN  KINUM:ZPAGE           $0094
47 0000          EXTERN  KIDEN:ZPAGE           $0096
48 0000          EXTERN  KDNUM:ZPAGE           $0098
49 0000          EXTERN  KDDEN:ZPAGE           $009A
50 0000          EXTERN  PERDTNUM:ZPAGE        $009C
51 0000          EXTERN  PERDTDEN:ZPAGE        $009E
52 0000          EXTERN  INT56:ZPAGE           $00A0
53 0000          EXTERN  FCS6:ZPAGE            $00A2
54 0000          EXTERN  TEMP1:ZPAGE           $00A4
55 0000          EXTERN  TEMP2:ZPAGE           $00A6
56 0000          EXTERN  TEMP3:ZPAGE           $00A8
57 0000          EXTERN  TEMP4:ZPAGE           $00AA
58 0000          EXTERN  KPTRM:ZPAGE           $00B4  LONGS
59 0000          EXTERN  KITRM:ZPAGE           $00BC
60 0000          EXTERN  KDTRM:ZPAGE           $00B8
61 0000          EXTERN  LTEMP1:ZPAGE          $00C0
62 0000          EXTERN  LTEMP2:ZPAGE          $00C4
63 0000          EXTERN  LTEMP3:ZPAGE          $00C8
64 0000          EXTERN  LTEMP4:ZPAGE          $00CC
65 0000          EXTERN  LTEMP5:ZPAGE          $00D0
66 0000          EXTERN  LTEMP6:ZPAGE          $00D4

```

67	0000		EXTERN	LTEMP7:2PAGE	\$00D8
68	0000		EXTERN	LTEMP8:2PAGE	\$00DC
69	0000		EXTERN	LTEMP9:2PAGE	\$00E0
70	0000		EXTERN	LTEMPA:2PAGE	\$00E4
71	0000		EXTERN	FCINT56:2PAGE	\$00E8
72	0000		EXTERN	INTFC56:2PAGE	\$00EC
73	0000		EXTERN	OLDDTY:2PAGE	\$00B0
74	0000		EXTERN	NEWDTY:2PAGE	\$00AC
75	0000		DOPID:		
76			***** OUTPUT LAST PERIOD RESULT AND DO KP TERM *****		
77					
78	0000	9601	LDAA	NEWDTY+1	OUTPUT PREVIOUS CALC.
79	0002	976C	STAA	PWDTY1	
80	0004	4F	CLRA		
81	0005	D631	LDAB	ADR1	GET CHANNEL 1 A/D RESULT.
82	0007	DD00	STD	ADRCX	DO KP TERM
83	0009	C610	LDAB	#\$10	FIRST START NEW A/D
84	000B	D730	STAB	ADCTL	CONVERSION
85	000D	DC00	LDD	CMNDVX	
86	000F	9300	SUBD	ADRCX	FORM ERROR TERM
87	0011	DD00	STD	ERRX	
88	0013	2B06	BMI	NFLAG1	SET UP SIGN FLAG IN TEMP3
89	0015	8600	LDAA	#\$00	POS
90	0017	9700	STAA	TEMP3	
91	0019	2004	BRA	NFLGG2	
92	001B	86FF	NFLAG1 LDAA	#\$FF	NEG
93	001D	9700	STAA	TEMP3	
94	001F	8680	NFLGG2 LDAA	#\$80	SET ALU FOR SMUL
95	0021	9744	STAA	ALUC	
96	0023	DC00	LDD	ERRX	
97	0025	DD45	STD	AREGH	
98	0027	8601	LDAA	#\$01	CLEAR ACF
99	0029	9749	STAA	ALUF	
100	002B	DC00	LDD	KPNUM	
101	002D	DD47	STD	BREGH	TRIGGER SMUL
102	002F	134901FC	WPMUL1 BRCLR	ALUF, #S01, WPMUL1	WAIT FOR ACF
103	0033	86C0	LDAA	#\$D0	SET ALU FOR SIDIV
104	0035	DD44	STD	ALUC	
105	0037	8601	LDAA	#\$01	CLEAR ACF
106	0039	9749	STAA	ALUF	
107	003B	DC00	LDD	KPDEN	
108	003D	DD45	STD	AREGH	TRIGGER SIDIV
109	003F	134901FC	WPDIV1 BRCLR	ALUF, #S01, WPDIV1	WAIT FOR ACF
110	0043	8601	LDAA	#\$01	CLEAR ACF
111	0045	9749	STAA	ALUF	
112	0047	86E8	LDAA	#\$E8	TRIGGER SFDIV
113	0049	DD44	STD	ALUC	
114	004B	134901FC	WPFDV1 BRCLR	ALUF, #S01, WPFDV1	WAIT FOR ACF
115	004F	DC40	LDD	CREGH	GET INT PART OF RESULT
116	0051	DD00	STD	KPTRM	
117	0053	DD00	STD	LTEMP1	
118	0055	DC42	LDD	CREGML	GET FRACTION
119	0057	DD02	STD	KPTRM+2	
120	0059	DD02	STD	LTEMP1+2	
121	005B	BD0361	JSR	ADLNG	NOW ADD TO OLDDTY
122	005E	BD007F	JSR	DOKIT	DO I TERM, ADD TO OLDDTY
123	0061	BD014F	JSR	DOKDT	DO D TERM, ADD TO OLDDTY
124	0064	DC00	LDD	NEWDTY	CHECK LIMITS
125	0066	2B0F	BMI	JAMZP	
126	0068	1A8300FF	CPD	#\$00FF	
127	006C	2B10	BMI	KXDONE	
128	006E	CC00FF	LDD	#\$00FF	JAM FF
129	0071	DD00	STD	NEWDTY	SATURATED HIGH
130	0073	DD00	STD	OLDDTY	
131	0075	2007	BRA	KXDONE	
132	0077	CC0000	JAMZP LDD	#\$0000	JAM 00
133	007A	DD00	STD	NEWDTY	SATURATED LOW
134	007C	DD00	STD	OLDDTY	
135	007E	39	KXDONE RTS		

```

136
137      * ROUTINE TO DO INTEGRAL TERM *
138
139 007F DC00      DOKIT   LDD      ADRCX      GET CURRENT CONVERSION
140 0081 D300      ADDD     ADR CXM1    FORM (ADRCX + ADR CXM1)/2
141 0083 04        LSRD
142 0084 DD00      STD      LTEMP2
143 0086 2507      BCS      JMHAFF
144 0088 CC0000     LDD      #S0000
145 008B DD02      STD      LTEMP2+2
146 008D 2005      BRA      INTKIE      FRACTIONAL PART OF FINAL ERROR
147 008F CC8000     JMHAFF LDD      #S8000    TERM WILL ALWAYS BE 0 or 0.5
148 0092 DD02      STD      LTEMP2+2
149 0094 DC00      INTKIE  LDD      CMNDVX
150 0096 9300      SUBD     LTEMP2
151 0098 1302800B  BRCLR    LTEMP2+2, #S80, NOFCN
152 009C DD00      STD      LTEMP2
153 009E 1A830000  CPD      #S0000
154 00A2 2F0B      BLE      NGFLG3
155 00A4 830001     SUBD     #S0001
156 00A7 DD00      NOFCN   STD      LTEMP2    CMNDVX - ((ADRCX + ADR CXM1)/2)
157 00A9 2B04      BMI      NGFLG3    SET UP SIGN FLAG IN TEMP3
158 00AB 8600      LDAA     #S00
159 00AD 2002      BRA      NGFLG2
160 00AF 86FF      NGFLG3 LDAA     #SFF
161 00B1 9700      NGFLG2 STAA     TEMP3
162 00B3 86C0      LDAA     #SD0
163 00B5 DD44      STD      ALUC
164 00B7 8601      LDAA     #S01
165 00B9 9749      STAA     ALUF
166 00BB CC0000     LDD      #S0000    SET UP KI NUMERATOR
167 00BE DD40      STD      CREGH
168 00C0 DC00      LDD      KINUM
169 00C2 DD42      STD      CREGML
170 00C4 DC00      LDD      KIDEN
171 00C6 DD45      STD      AREGH
172 00C8 134901FC  WIDIV1 BRCLR    ALUF, #S01, WIDIV1    TRIGGER SIDIV
173 00CC 8601      LDAA     #S01    WAIT FOR ACF
174 00CE 9749      STAA     ALUF    CLEAR ACF
175 00D0 86E8      LDAA     #SE8
176 00D2 DD44      STD      ALUC
177 00D4 134901FC  WIFDV1 BRCLR    ALUF, #S01, WIFDV1    TRIGGER SFDIV
178 00D8 DC40      LDD      CREGH    WAIT FOR ACF
179 00DA DD00      STD      LTEMP3
180 00DC DC42      LDD      CREGML
181 00DE DD02      STD      LTEMP3+2
182 00E0 86C0      LDAA     #SD0
183 00E2 DD44      STD      ALUC
184 00E4 8601      LDAA     #S01
185 00E6 9749      STAA     ALUF
186 00E8 CC0000     LDD      #S0000    SET UP PERDTNUM
187 00EB DD40      STD      CREGH
188 00ED DC00      LDD      PERDTNUM
189 00EF DD42      STD      CREGML
190 00F1 DC00      LDD      PERDTDEN
191 00F3 DD45      STD      AREGH
192 00F5 134901FC  WIDIV2 BRCLR    ALUF, #S01, WIDIV2    TRIGGER SIDIV
193 00F9 8601      LDAA     #S01    WAIT FOR ACF
194 00FB 9749      STAA     ALUF    CLEAR ACF
195 00FD 86E8      LDAA     #SE8
196 00FF DD44      STD      ALUC
197 0101 134901FC  WIFDV2 BRCLR    ALUF, #S01, WIFDV2    TRIGGER SFDIV
198 0105 DC40      LDD      CREGH    WAIT FOR ACF
199 0107 DD00      STD      LTEMP4
200 0109 DC42      LDD      CREGML
201 010B DD02      STD      LTEMP4+2
202 010D DC00      LDD      LTEMP3
203 010F DD00      STD      LTEMP5
204 0111 DC02      LDD      LTEMP3+2    NOW FORM LTEMP2*LTEMP3*LTEMP4

```

205	0113	DD02	STD	LTEMP5+2	
206	0115	DC00	LDD	LTEMP4	
207	0117	DD00	STD	LTEMP6	
208	0119	DC02	LDD	LTEMP4+2	
209	011B	DD02	STD	LTEMP6+2	
210	011D	9600	LDAA	TEMP3	SAVE SIGN FLAG
211	011F	9700	STAA	TEMP4	AND USE TEMP3 AS A FLAG
212	0121	8600	LDAA	#S00	FOR LTEMP6 BEING POSITIVE
213	0123	9700	STAA	TEMP3	
214	0125	BD023A	JSR	MULLNG	DO LTEMP3*LTEMP4 (PERDT*KI)
215	0128	DC00	LDD	LTEMP7	NOW PUT RESULT IN LTEMP5
216	012A	DD00	STD	LTEMP5	
217	012C	DC02	LDD	LTEMP7+2	
218	012E	DD02	STD	LTEMP5+2	
219	0130	9600	LDAA	TEMP4	RETRIEVE SIGN FLAG
220	0132	9700	STAA	TEMP3	
221	0134	DC00	LDD	LTEMP2	
222	0136	DD00	STD	LTEMP6	ERROR FOR KI TERM
223	0138	DC02	LDD	LTEMP2+2	
224	013A	DD02	STD	LTEMP6+2	
225	013C	BD023A	JSR	MULLNG	DO RESULT*LTEMP2
226	013F	DC00	LDD	LTEMP7	
227	0141	DD00	STD	LTEMP1	
228	0143	DD00	STD	KITRM	
229	0145	DC02	LDD	LTEMP7+2	
230	0147	DD02	STD	LTEMP1+2	
231	0149	DD02	STD	KITRM+2	ADD KI TERM INTO NEWDTY
232	014B	BD0361	JSR	ADLNG	KITERM DONE
233	014E	39	RTS		RETURN
234					
235		*****	ROUTINE TO DO KD TERM	*****	
236					
237	014F	DC00	DOKDT LDD	ERRX	FORM (ERRX - ERRM3X)
238	0151	9300	SUBD	ERRM3X	+ 3*(ERRM1X - ERRM2X)
239	0153	DD00	STD	TEMP1	
240	0155	DC00	LDD	ERRM1X	
241	0157	9300	SUBD	ERRM2X	
242	0159	DD45	STD	AREGH	FORM 3*(ERRM1X - ERRM2X)
243	015B	8680	LDAA	#S80	
244	015D	9744	STAA	ALUC	
245	015F	8601	LDAA	#S01	
246	0161	9749	STAA	ALUF	
247	0163	CC0003	LDD	#S0003	
248	0166	DD47	STD	BREGH	
249	0168	134901FC	WDMULO BRCLR	ALUF, #S01, WDMULO	WAIT FOR ACF
250	016C	DC42	LDD	CREGML	
251	016E	D300	ADDD	TEMP1	
252	0170	DD00	STD	LTEMPA	
253	0172	2B02	BMI	NGFLGSO	SET UP SIGN FLAG IN TEMP3
254	0174	2006	BRA	POSGN	
255	0176	86FF	NGFLGSO LDAA	#SFF	
256	0178	9700	STAA	TEMP3	
257	017A	2004	BRA	KDFLGD	
258	017C	8600	POSGN LDAA	#S00	
259	017E	9700	STAA	TEMP3	
260	0180	CC0000	KDFLGD LDD	#S0000	
261	0183	DD02	STD	LTEMPA+2	DONE
262	0185	8600	LDAA	#S00	FORM 6*PERDTNUM
263	0187	9744	STAA	ALUC	
264	0189	8601	LDAA	#S01	
265	018B	9749	STAA	ALUF	
266	018D	CC0006	LDD	#S0006	
267	0190	DD45	STD	AREGH	
268	0192	DC00	LDD	PERDTNUM	
269	0194	DD47	STD	BREGH	
270	0196	134901FC	WDMUL1 BRCLR	ALUF, #S01, WDMUL1	WAIT FOR ACF
271	019A	DC42	LDD	CREGML	
272	019C	DD00	STD	TEMP2	
273	019E	86C0	NOFCND LDAA	#SD0	SET ALU FOR SIDIV TO FORM

274	01A0	DD44	STD	ALUC	KDNUM/KDDEN
275	01A2	8601	LDAA	#\$01	CLEAR ACF
276	01A4	9749	STAA	ALUF	
277	01A6	CC0000	LDD	#\$0000	SET UP KD NUMERATOR
278	01A9	DD40	STD	CREGH	
279	01AB	DC00	LDD	KDNUM	
280	01AD	DD42	STD	CREGML	
281	01AF	DC00	LDD	KDDEN	
282	01B1	DD45	STD	AREGH	TRIGGER SIDIV
283	01B3	134901FC	WDDIV1	BRCLR	ALUF, #\$01, WDDIV1
284	01B7	8601	LDAA	#\$01	WAIT FOR ACF
285	01B9	9749	STAA	ALUF	CLEAR ACF
286	01BB	86E8	LDAA	#\$E8	TRIGGER SFDIV
287	01BD	DD44	STD	ALUC	
288	01BF	134901FC	WDFDV1	BRCLR	ALUF, #\$01, WDFDV1
289	01C3	DC40	LDD	CREGH	WAIT FOR ACF
290	01C5	DD00	STD	LTEMP8	
291	01C7	DC42	LDD	CREGML	
292	01C9	DD02	STD	LTEMP8+2	
293	01CB	86C0	LDAA	#\$D0	SET ALU FOR SIDIV TO FORM
294	01CD	DD44	STD	ALUC	PERDTEN/(PERDTNUM*6)
295	01CF	8601	LDAA	#\$01	CLEAR ACF
296	01D1	9749	STAA	ALUF	
297	01D3	CC0000	LDD	#\$0000	SET UP PERDTNUM
298	01D6	DD40	STD	CREGH	
299	01D8	DC00	LDD	PERDTEN	
300	01DA	DD42	STD	CREGML	
301	01DC	DC00	LDD	TEMP2	
302	01DE	DD45	STD	AREGH	TRIGGER SIDIV
303	01E0	134901FC	WDDIV2	BRCLR	ALUF, #\$01, WDDIV2
304	01E4	8601	LDAA	#\$01	WAIT FOR ACF
305	01E6	9749	STAA	ALUF	CLEAR ACF
306	01E8	86E8	LDAA	#\$E8	TRIGGER SFDIV
307	01EA	DD44	STD	ALUC	
308	01EC	134901FC	WDFDV2	BRCLR	ALUF, #\$01, WDFDV2
309	01F0	DC40	LDD	CREGH	WAIT FOR ACF
310	01F2	DD00	STD	LTEMP9	
311	01F4	DC42	LDD	CREGML	
312	01F6	DD02	STD	LTEMP9+2	
313	01F8	DC00	LDD	LTEMP8	NOW FORM LTEMPA*LTEMP8*LTEMP9
314	01FA	DD00	STD	LTEMP5	
315	01FC	DC02	LDD	LTEMP8+2	
316	01FE	DD02	STD	LTEMP5+2	
317	0200	DC00	LDD	LTEMP9	
318	0202	DD00	STD	LTEMP6	
319	0204	DC02	LDD	LTEMP9+2	
320	0206	DD02	STD	LTEMP6+2	
321	0208	9600	LDAA	TEMP3	SAVE SIGN FLAG
322	020A	9700	STAA	TEMP4	AND USE TEMP3 AS A FLAG
323	020C	8600	LDAA	#\$00	FOR LTEMP6 BEING POSITIVE
324	020E	9700	STAA	TEMP3	
325	0210	BD023A	JSR	MULLNG	DO LTEMP8*LTEMP9
326	0213	DC00	LDD	LTEMP7	NOW PUT RESULT IN LTEMP5
327	0215	DD00	STD	LTEMP5	
328	0217	DC02	LDD	LTEMP7+2	
329	0219	DD02	STD	LTEMP5+2	
330	021B	9600	LDAA	TEMP4	RETRIEVE SIGNED ERROR
331	021D	9700	STAA	TEMP3	
332	021F	DC00	LDD	LTEMPA	
333	0221	DD00	STD	LTEMP6	ERROR FOR KD TERM
334	0223	DC02	LDD	LTEMPA+2	
335	0225	DD02	STD	LTEMP6+2	
336	0227	BD023A	JSR	MULLNG	DO RESULT*LTEMPA
337	022A	DC00	LDD	LTEMP7	
338	022C	DD00	STD	LTEMP1	
339	022E	DD00	STD	KDTRM	
340	0230	DC02	LDD	LTEMP7+2	
341	0232	DD02	STD	LTEMP1+2	
342	0234	DD02	STD	KDTRM+2	

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343 0236 BD0361      JSR      ADLNG      ADD KD TERM INTO NEWDTY
344 0239 39          RTS              KDTerm DONE
345
346      * SUBROUTINE TO MULTIPLY LONGS(INTEGER & FRACTION) *
347      * LTEMP5*LTEMP6=LTEMP7 ONLY LTEMP6 CAN HAVE      *
348      * A NEGATIVE TERM TO HANDLE.                      *
349
350 023A 8680      MULLNG  LDAA      #S80          SET ALU FOR SMUL
351 023C 9744      STAA     ALUC          AND MULTIPLY INTS
352 023E DC00      LDD      LTEMP5
353 0240 DD45      STD      AREGH
354 0242 8601      LDAA     #S01          CLEAR ACF
355 0244 9749      STAA     ALUF
356 0246 DC00      LDD      LTEMP6
357 0248 DD47      STD      BREGH        TRIGGER SMUL
358 024A 134901FC  WMULL1  BRCLR    ALUF,#S01,WMULL1  WAIT FOR ACF
359 024E DC42      LDD      CREGML
360 0250 DD00      STD      INT56
361 0252 8601      LDAA     #S01          CLEAR ACF AND DO NEXT MULT
362 0254 9749      STAA     ALUF
363 0256 8680      LDAA     #S80          TEST TEMP3 SIGN
364 0258 9500      BITA     TEMP3        SEE IF ERR IS NEG
365 025A 2B12      BMI      NEGFRAC     TERM IS NEGATIVE
366 025C DC02      LDD      LTEMP6+2    GET FRAC NOT NEG
367 025E DD47      STD      BREGH        TRIGGER SMUL
368 0260 134901FC  WMULL2  BRCLR    ALUF,#S01,WMULL2  WAIT FOR ACF
369 0264 DC40      LDD      CREGH        SCALE AND STORE
370 0266 DD00      STD      INTFC56
371 0268 DC42      LDD      CREGML
372 026A DD02      STD      INTFC56+2
373 026C 2022      BRA      NXFRAC
374 026E CC0000    NEGFRAC  LDD      #S0000    NEGATE FRAC
375 0271 9302      SUBD     LTEMP6+2
376 0273 DD47      STD      BREGH        TRIGGER SMUL
377 0275 134901FC  WMULL3  BRCLR    ALUF,#S01,WMULL3  WAIT FOR ACF
378 0279 CC0000    LDD      #S0000    NEGATE RESULT
379 027C 9340      SUBD     CREGH        SCALE AND STORE
380 027E 2B02      BMI      INTFIX1
381 0280 2003      BRA      INTFIX2
382 0282 C30001    INTFIX1  ADDD     #S0001
383 0285 DD00      INTFIX2  STD      INTFC56
384 0287 CC0000    LDD      #S0000
385 028A 9342      SUBD     CREGML
386 028C DD02      STD      INTFC56+2
387 028E 8600      LDAA     #S00
388 0290 DC02      NXFRAC  LDD      LTEMP5+2    GET FRAC AND MULTIPLY
389 0292 DD45      STD      AREGH        WITH POSSIBLE NEG INT
390 0294 8601      LDAA     #S01          CLEAR ACF
391 0296 9749      STAA     ALUF
392 0298 8600      LDAA     #S00
393 029A DC00      LDD      LTEMP6
394 029C DD47      STD      BREGH        TRIGGER SMUL
395 029E 134901FC  WMULL4  BRCLR    ALUF,#S01,WMULL4  WAIT FOR ACF
396 02A2 8680      LDAA     #S80
397 02A4 9500      BITA     TEMP3
398 02A6 2A0F      BPL      DFXINT
399 02A8 8680      LDAA     #S80          SEE IF SIGN OVERFLOW
400 02AA 9545      BITA     AREGH        ON FRACTION
401 02AC 2B02      BMI      FXINT
402 02AE 2007      BRA      DFXINT
403 02B0 CC0000    FXINT  LDD      #S0000
404 02B3 9340      SUBD     CREGH
405 02B5 DD40      STD      CREGH
406 02B7 DC40      DFXINT  LDD      CREGH        THIS SCALES FRAC
407 02B9 2B02      BMI      NFFIX
408 02BB 2003      BRA      PFFIX
409 02BD C30001    NFFIX  ADDD     #S0001
410 02C0 DD00      PFFIX  STD      FCINT56
411 02C2 DC42      LDD      CREGML

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412	02C4 DD02		STD	FCINT56+2	
413	02C6 8601		LDAA	#\$01	NOW DO FRAC*FRAC
414	02C8 9749		STAA	ALUF	CLEAR ACF
415	02CA 8600		LDAA	#\$00	
416	02CC 9744		STAA	ALUC	SET UNSIGNED MULT FOR FRACS
417	02CE 8680		LDAA	#\$80	TEST ERR SIGN
418	02D0 9500		BITA	TEMP3	SEE IF ERR IS NEG
419	02D2 2B0E		BMI	NFCFRAC	TERM IS NEGATIVE
420	02D4 DC02		LDD	LTEMP6+2	GET FRAC NOT NEG
421	02D6 DD47		STD	BREGH	TRIGGER SMUL
422	02D8 134901FC	WMULL5	BRCLR	ALUF, \$01, WMULL5	WAIT FOR ACF
423	02DC DC40		LDD	CREGH	SCALE AND STORE
424	02DE DD00		STD	FC56	
425	02E0 2012		BRA	SUMMUL	
426	02E2 CC0000	NFCFRAC	LDD	#\$0000	NEGATE FRAC
427	02E5 9302		SUBD	LTEMP6+2	
428	02E7 DD47		STD	BREGH	TRIGGER SMUL
429	02E9 134901FC	WMULL6	BRCLR	ALUF, \$01, WMULL6	WAIT FOR ACF
430	02ED CC0000		LDD	#\$0000	NEGATE RESULT
431	02F0 9340		SUBD	CREGH	SCALE AND STORE
432	02F2 DD00		STD	FC56	
433	02F4 DC00	SUMMUL	LDD	INT56	NOW SUMM ALL PRODUCTS
434	02F6 D300		ADDD	FCINT56	INTS ARE ALL SIGNED
435	02F8 D300		ADDD	INTFC56	CAN JUST ADD UP
436	02FA DD00		STD	LTEMP7	
437	02FC 8680		LDAA	#\$80	TEST ERRX SIGN
438	02FE 9500		BITA	TEMP3	SEE IF FRACS ARE NEG
439	0300 2B22		BMI	SUMNFC	FRACS ARE NEGATIVE
440	0302 DC02		LDD	FCINT56+2	POSITIVE
441	0304 D302		ADDD	INTFC56+2	
442	0306 2502		BCS	FCCAR1	
443	0308 2009		BRA	SUMFC1	
444	030A 8F	FCCAR1	XGDX		SAVE SUM
445	030B CC0001		LDD	#\$0001	ADD CARRY INTO INT
446	030E D300		ADDD	LTEMP7	
447	0310 DD00		STD	LTEMP7	
448	0312 8F		XGDX		RETRIEVE SUM
449	0313 D300	SUMFC1	ADDD	FC56	
450	0315 DD02		STD	LTEMP7+2	
451	0317 2502		BCS	FCCAR2	
452	0319 2045		BRA	SMFCDP	
453	031B CC0001	FCCAR2	LDD	#\$0001	ADD CARRY INTO INT
454	031E D300		ADDD	LTEMP7	
455	0320 DD00		STD	LTEMP7	
456	0322 203C		BRA	SMFCDP	
457	0324 CC0000	SUMNFC	LDD	#\$0000	COMPLEMENT NEG FRACS
458	0327 9302		SUBD	FCINT56+2	
459	0329 DD02		STD	FCINT56+2	
460	032B CC0000		LDD	#\$0000	
461	032E 9302		SUBD	INTFC56+2	
462	0330 DD02		STD	INTFC56+2	
463	0332 CC0000		LDD	#\$0000	
464	0335 9300		SUBD	FC56	
465	0337 DD00		STD	FC56	
466	0339 DC02		LDD	FCINT56+2	NEGATIVE
467	033B D302		ADDD	INTFC56+2	
468	033D 2502		BCS	FCCAR3	REMEMBER SIGN BIT!!
469	033F 2009		BRA	SUMFC2	
470	0341 8F	FCCAR3	XGDX		SAVE SUM
471	0342 CCFFFF		LDD	#\$FFFF	ADD BORROW INTO INT
472	0345 D300		ADDD	LTEMP7	
473	0347 DD00		STD	LTEMP7	
474	0349 8F		XGDX		RETRIEVE SUM
475	034A D300	SUMFC2	ADDD	FC56	
476	034C DD02		STD	LTEMP7+2	
477	034E 2502		BCS	FCCAR4	
478	0350 2007		BRA	SMFCDN	
479	0352 CCFFFF	FCCAR4	LDD	#\$FFFF	ADD BORROW INTO INT
480	0355 D300		ADDD	LTEMP7	

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481 0357 DD00          STD      LTEMP7
482 0359 CC0000      SMFCDN  LDD      $S0000          CONVERT BACK TO NEG
483 035C 9302          SUBD     LTEMP7+2
484 035E DD02          STD      LTEMP7+2
485 0360 39          SMFCDP  RTS
486
487
488          * SUBROUTINE TO ADD INTEGER AND FRACTION IN LTEMP1 TO OLDDTY *
489
490 0361 8680      ADLNG  LDAA      $S80          TEST ERRX SIGN
491 0363 9500          BITA      TEMP3
492 0365 2B19          BMI      KXNEG          TERM IS NEGATIVE
493 0367 DC00          LDD      LTEMP1          GET INT PART
494 0369 D300          ADDD     OLDDTY          ADD AND STORE INT
495 036B DD00          STD      NEWDTY
496 036D DC02          LDD      LTEMP1+2          GET FRAC PART
497 036F D302          ADDD     OLDDTY+2          ADD AND STORE FRAC
498 0371 DD02          STD      NEWDTY+2
499 0373 2502          BCS      INCINT
500 0375 201E          BRA      ADDONE
501 0377 CC0001      INCINT  LDD      $S0001          ADD CARRY FROM FRAC
502 037A D300          ADDD     NEWDTY
503 037C DD00          STD      NEWDTY
504 037E 2015          BRA      ADDONE
505 0380 DC00      KXNEG  LDD      LTEMP1          GET INT PART
506 0382 D300          ADDD     OLDDTY          ADD AND STORE INT
507 0384 DD00          STD      NEWDTY
508 0386 DC02          LDD      LTEMP1+2          GET FRAC PART
509 0388 D302          ADDD     OLDDTY+2          ADD AND STORE FRAC
510 038A DD02          STD      NEWDTY+2          ACTUALLY A SUBTRACTION
511 038C 2507          BCS      ADDONE
512 038E CCFFFF      DECINT  LDD      $FFFFFF          SUBTRACT BORROW FROM FRAC
513 0391 D300          ADDD     NEWDTY
514 0393 DD00          STD      NEWDTY
515 0395 DC00      ADDONE  LDD      NEWDTY          UPDATE OLDDTY FOR NEXT TERM
516 0397 DD00          STD      OLDDTY          OR FINISH
517 0399 DC02          LDD      NEWDTY+2
518 039B DD02          STD      OLDDTY+2
519 039D 39          RTS          RETURN TO CALLING ROUTINE
520 039E          END

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Errors:  None          #####
Bytes:   926          # DOPID #
CRC:     EC21          #####

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